Residual stress field of HIPed silicon nitride rolling elements

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Abstract: The residual stress field of HIPed Si_3N_4 rolling elements were studied. Two kinds of HIPed Si_3N_4 ball blanks self-finished at different nominal lapping loads ranging from 1.3kgf/ball to 10.87kgf/ball and four kinds of commercially finished ½″ (12.7mm) HIPed Si_3N_4 balls before, during and after RCF tests were investigated. The experimental results showed that in the finishing process of HIPed Si_3N_4 rolling elements, the surface and subsurface compressive residual stress induced is proportional to the lapping load applied. There was initially a high compressive residual stress layer on the HIPed Si_3N_4 ball blanks and this layer is mostly removed during the finishing process. During the rolling contact fatigue process of HIPed Si_3N_4 rolling elements, the residual stresses on the rolling track will change dramatically as RCF proceeds.

Keywords: A. Finishing; D. Si_3N_4; C. Fatigue; B. X-ray method; Residual stress

1. Introduction

Hybrid precision ball-bearings (with Hot Isostatically Pressed (HIPed) silicon nitride balls as the rolling elements and steel inner and outer rings) are used extensively in machine tools and other applications involving high speeds or extreme operating conditions. The material properties — low density, high elastic modulus, corrosion resistance, and temperature resistance — give significant performance advantages [1, 2]. Since these rolling elements are subjected to high cyclic contact stresses during service, the surface and subsurface residual stresses are highly concerned.

Generally, it was considered that the presence of a deep zone of surface finishing residual compressive stresses in mechanical and structural ceramics can be beneficial. A requirement is to maximize the surface residual stress zone depth and minimize the finishing induced crack size, so as to ensure that the crack is embedded well inside the residual compressive stress layer [3].

The finishing process parameters have influences on residual stresses. Chandrasekar et al [3, 4] 's study on the lapping of ceramics showed that the maximum compressive residual stress as well as the depth of the compressively stressed zone increases with increasing lapping pressure; lapping with softer abrasives and smaller particles results in lower compressive residual stresses near the surface; a larger grit size will result in larger residual stresses. Stolarski and Tobe [5] 's study on finishing 6.5mm diameter HIPed silicon nitride balls indicated that the residual compressive stress decreases as the amount of material removed grows. Initially, the rate of residual stress decrease is fairly high but this reduces as the removal of material progresses. A survey of finished HIPed 12.7 mm diameter silicon nitride balls from 7 different manufacturers showed that the residual stresses were all compressive and ranged from 54MPa to 111MPa [6].

The residual stresses may be related to fatigue failure. Studies had shown that there is a dormant period between each successive crack advancement during which the residual stress and a plastic component are each built up in a cumulative manner leading to eventual failure [7]. The dynamic relationship between residual stress development and fatigue fracture formation under cyclic loading was investigated by Pruitt and Suresh, direct and in-situ measurements of cyclic stress fields ahead of fatigue flaws in a model amorphous solid subjected to far-field cyclic compression loading, to illustrate how the residual tensile stresses developing within the cyclic damage zone cause crazes to form along the plane of the fatigue crack in the direction normal to the far-field compression axis [8]. The residual stresses around the wear track of an upper ball of silicon nitride/silicon nitride contact after a rolling 4-ball test under maximum contact stress of 7.6GPa for 150 million stress cycles were measured. It was shown that the residual stress values were different at the different locations and directions on the wear track [6]. In an earlier study on the residual stresses in the delamination area using different measurement parameter settings, the correlation of compressive residual stresses with failure depth suggested a shear stress type of failure [9, 10].

In the present study, the residual stress change on two kinds of HIPed Si_3N_4 ball blanks self-finished at different nominal lapping loads ranging from 1.3kgf/ball to 10.87kgf/ball were investigated. The residual stresses on four kinds of commercially finished ½″ (12.7mm) HIPed Si_3N_4 balls before, during and after RCF tests were also investigated.

2. Experimental Procedure

2.1 Finishing Test

Two kinds of commercial ½″ (12.7 mm) HIPed Si_3N_4 ball blanks have been used, and designated as BBA and BBB. The individual manufacturing processes and measured characteristics of the two kinds of ball blanks are listed in Table 1. Finishing tests were conducted on a novel eccentric lapping machine, whose detailed description and the finishing processes can be found in earlier publications [11, 12] [13]. The lapping speed was 169 rpm, diamond particle size was 45 μm and the diamond paste concentration was 1g:30ml (1g diamond paste with 30ml lapping fluid). The lapping loads were ranging from an average of 1.3kgf/ball to 10.87kgf/ball. In order to eliminate the influences of surface irregularities and surface roughness on the measurement results of residual stresses, after lapping balls were polished at light load.

2.2 RCF Test

Rolling Contact Fatigue (RCF) tests were conducted on four kinds of commercially finished HIPed Si_3N_4 bearing balls (grade 5 or grade 10) procured directly from the manufacturers. They were designated as A, B, C, D and the measured geometric and material properties are listed in Table 2 The RCF tests were performed on a Plint TE92/HS Microprocessor Controlled Rotary Tribometer configured as a high-speed rolling 4-ball machine. More detailed description about this test machine can be found in an earlier publication [14]. All tests were conducted at a maximum contact stress of 6.58 GPa and at the test machine shaft speed 10,000 rpm in fully lubricated condition using Shell Talpa 20 as lubricant oil, with HIPed Si_3N_4 ball as upper ball and three standard steel bearing balls (specification: 0.5″ ball Reference RB12.7/310995A, material: AISI 52100 bearing steel) as lower balls. Normally, tests were stopped before reaching the set time (hours) due to the failure of one lower steel ball (typically a fatigue spall). In this situation three new steel balls and fresh lubricant oil were fitted and the test continued. By changing lower steel balls, the upper Si_3N_4 testing ball could exceed the set testing time or contact stress cycles. At the end of each test, no typical fatigue spall occurred on any of the upper Si_3N_4 ball, and the wear on the rolling track was also very small, in the range of $0.3\sim3\times10^{-10}$ m^3. More detailed description on the RCF test procedure can be found in an earlier publication [15].

2.3 Residual Stress Measurement

The residual stresses induced by the finishing process and the residual stress change occurring during the RCF test were measured by the X-ray diffraction method. When a stress is applied to a material, the inter-atomic distance in the crystal will be extended or compressed within the elastic limit of the material in proportion to the stress. The X-ray diffraction method measures the variation of the inter-planar spacing in the crystal from the variation of the X-ray diffraction angle. By using Bragg's equation, strain is calculated, and then stress is calculated from strain. A detailed description of the X-ray diffraction method can be found in reference [16].

The residual stress measurement was conducted using a Rigaku Rint 2500 X-Ray Diffractometer. Three sample balls to be measured were fitted in a ball holder with the area intended to be measured on the top and centre of each hole of the ball holder, and the ball holder was vertically fastened to a jig. The jig can be moved along X, Y, Z axes and rotated around Z axis. The small gap between the sample ball and the hole was sealed with tape around the edge of the hole, in order to eliminate any clamping force applied to the sample ball.

The parameter setting of the Rigaku Rint 2500 X-Ray Diffractormeter is as following: The X-ray source is Cr $K\alpha 1$ at 40 kV and 250 mA. The diameter of collimator is 1.0 mm. The diffraction angle is 125° and the scan range is from 123° to 127°, with a step angle of 0.002° and sampling time 100 sec. The material properties for HIPed Si_3N_4 were chosen as Young's modulus 310000 MPa and Poisson's ratio 0.26.

In order to investigate the residual stress field change during the RCF test, two points on each sample were measured: on the rolling track (Fig 1 (a)) and outside the rolling track at the centre of the rolling track circle (Fig 1 (b)). It was anticipated that this point at the centre of the rolling track circle (Fig 1 (b)) had endured least stress during the RCF test, because half of the ball surface was in the collet (Fig 1 (c)) inside the shaft of the test machine during the RCF test and may have endured more stresses than this point.

The depth of the measurement was about 30 μm, and this was dependent on the X-ray source which penetrated the material. The area of the measurement was a circular area with a diameter of 1 mm which was determined by the diameter of the collimator. The direction of the measurement at the point on the rolling track was parallel to the rolling track (Fig 1 (a)). The direction of the measurement on the finished ball surface and on the point at the centre of the rolling track circle (Fig 1 (b)) is not relevant. Each measurement took about 30 minutes.

3. Experimental Results and Discussion

3.1 Finishing Process Induced Residual Stresses

Table 3 is the residual stress measurement results on self-finished balls. Two results can be drawn from this investigation. The first result is that there are initially compressive residual stresses on the ball blank surfaces due to previous HIP processes. This compressive residual stress layer extends approximately 0.3 mm from the ball blank surface with a final diameter of 12.7 mm ball (ball blank diameter was 13.25~13.5). Very high compressive value is evident at the ball blank surface. This gradually reduces towards the core of the ball. This residual stress layer will be partly or entirely removed during the finishing process.

This is supported by the very high compressive value (-803.7 MPa) measured on the BBB blank with a diameter of 13.50 mm. After lapping to a diameter of 13.40 mm the compressive value had reduced to –237.7 MPa and finally after lapping and polishing to a diameter of 13.05 mm, the compressive value dropped to –41.4 MPa. For BBA blanks, the measured compressive residual stress values were –149.1 MPa before polishing and –117.7 MPa after polishing. The measured compressive residual stress values for the BBA blanks were not very high. There are two possible reasons for this. One possibility is that the previous manufacturing process for BBA was directly HIPed which introduced less compressive residual stress than the Sinter + HIPed process employed for BBB. Another possibility is that after the directly HIPed process, the BBA were roughly ground before being supplied as ball blanks. The most compressive residual layer would then have been removed during this rough grinding process. This compressive residual stress is concentrated near the surface layer of the ball blank. This is supported both from the measurement results of the BBB ball, –41.36MPa at a diameter of 13.051 and from the measurement results of the BBA ball, –11.95MPa at a diameter of 12.703. They were both lapped at a load of 1.3kgf/ball, removed a layer of 0.45~0.55 mm in diameter, assuming the residual stress change induced under this light lapping load can be ignored. A previous investigation by Stolarski and Tobe [5] on 6.5 mm nominal diameter balls also reported that the residual compressive stress decreases as the amount of material removed grows.

The second result is that higher lapping load will generate higher compressive residual stresses on the balls. The residual stresses were measured on BBA lapped under different loads to nearly the final diameter of 12.7 mm. In order to eliminate the influences of surface profile and surface damage from the measured values of residual stresses, balls lapped under different loads were polished. The results showed that there was almost a linear increase of the compressive residual stress as the lapping load increased (Fig 2). Under a lapping load of 1.3 kgf/ball, the residual stress was –11.95 MPa, and at the highest lapping load of 10.87 kgf/ball, the residual stress was –142.34 MPa. The residual stress change from the lowest lapping load to the highest lapping load was only about –130 MPa.

It was shown that under the highest lapping load of 10.87 kgf/ball, severe surface and subsurface damage occurred, although the lapping rate was not high [13]. The recommended lapping load is 4.37kgf/ball or less. Under these circumstances, the residual stresses induced by the lapping process will be within –100 MPa.

3.2 The Change of Residual Stress Distribution during RCF Test

The surface and subsurface residual stress values for these four kinds of balls before RCF tests are listed in Table 4. The characteristics of these balls are listed in Table 2. The residual stress values for these balls are all compressive before RCF test ranging from -132.857 MPa to -21.276 MPa.

The residual stress values during and after RCF tests were listed in Table 5. It was found from Table 5 that the residual stress at the rolling track had changed greatly during the RCF test process. The residual stress at the rolling track for the B series after 67 hours RCF test is -269.925 MPa and after 100 hours RCF test it becomes 174.208 MPa, an absolute value change of nearly 450 MPa. To verify this, another point was measured on the rolling track for the B series after 67 hours RCF test, and the result was very close (-277.054 MPa). The residual stress at the rolling track for C series after 44 hours RCF test is -45.543 MPa and after 110 hours RCF test it becomes 133.959 MPa.

The assumption here is: during the RCF test, the residual stress on the rolling track will first become compressive, then change to tensile. When the tensile residual stress is high, it is near failure. The time period for this change of residual stress is different for different kinds of HIPed Si_3N_4 rolling elements, depending on the material properties, applied load etc.. If this phenomenon does exist, the residual stress measurement could be used to predict the failure.

Another finding from the measurement results is that the residual stress change zone during RCF test is far beyond the rolling track. It was anticipated that the point at the centre of the rolling track circle (Fig 1 (b)) had endured least stress during RCF test. This point is 4 mm away from the rolling track. After RCF tests, the residual stress values at this point in all of the samples have become tensile, and the absolute residual stress value change is around 100 MPa for each sample no matter whether the RCF test is 44 hour or over 100 hours. It is likely that during RCF test, the rolling track surface and subsurface become compressive thus causing nearby tensile residual stress. The residual stress on the rolling track will change greatly during RCF test. In contrast, the residual stress at the nearby area will probably not change very much: for the B series from 57.699 MPa at 67 hours to 23.674 MPa at 100 hours and for the C series from 36.224 MPa at 44 hours to 63.965 MPa at 110 hours, as shown in Table 5.

4. Concluding Remarks

In the finishing process of HIPed Si_3N_4 rolling elements, the surface and subsurface compressive residual stress induced is proportional to the lapping load applied. The value of the compressive residual stress induced is not high, even at extreme high lapping load 10.87kgf/ball only –130MPa. There was initially a high compressive residual stress layer on the HIPed Si_3N_4 ball blanks and this layer is mostly removed during the finishing process. During the rolling contact fatigue process of HIPed Si_3N_4 rolling elements, the residual stresses on the rolling track will change dramatically as RCF proceeds. There is a possibility to use this phenomena to predict RCF failure, although much more theoretical and and experimental studies are needed.

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Table 5 Residual stress measurement results after RCF test

Fig 1 Residual stress measuring points

Fig 2 Residual stress versus lapping load

	BBA (HIPed Si_3N_4 ball blank from manufacturer A)	BBB (HIPed Si_3N_4 ball blank from manufacturer B)
Manufacturing Process	Directly HIPed, then rough-ground	Sinter + HIPed
Density (kg/m^3)	3160	3237
Ball Diameter (mm)	13.255	13.46 ~ 13.50
Ball Roundness Variation (mm)	0.001	0.030 ~0.075
Surface Roughness R_a (μm)	0.202	2.645
Surface Hardness (Vickers Hardness Number, Hv 10)	1682	1532

Table 1 Characteristics of the two kinds of HIPed silicon nitride ball blanks

Samples	Diameter mm	Surface roughness R_a μm	Density (kg/m^3)	Surface Hardness (Hv 10)
A	12.7004	0.005	3214	1505
B	12.7007	0.016	3238	1560
C	12.6994	0.003	3226	1478
D	12.6998	0.002	3166	1619

Table 2 The measured geometric and material properties of RCF test samples A~D

Description of the ball	Diameter (mm)	Residual stress value (MPa)
BBA as procured	13.255	-149.11(±)29.29
BBA polished from as procured	13.252	-117.721(±)40.69
BBA 10.87kgf/ball lapped, then polished	12.698	-142.341(±)38.91
BBA 4.37kgf/ball lapped, then polished	12.698	-92.1(±)50.71
BBA 3.16kgf/ball lapped, then polished	12.704	-78.321(±)36.20
BBA 1.3kgf/ball lapped, then polished	12.703	-11.954(±)34.21
BBB as procured	13.5	-803.699(±)58.28
BBB 1.85kgf/ball lapped	13.4	-237.667(±)47.32
BBB 1.3kgf/ball lapped, then polished	13.051	-41.357(±)37.10

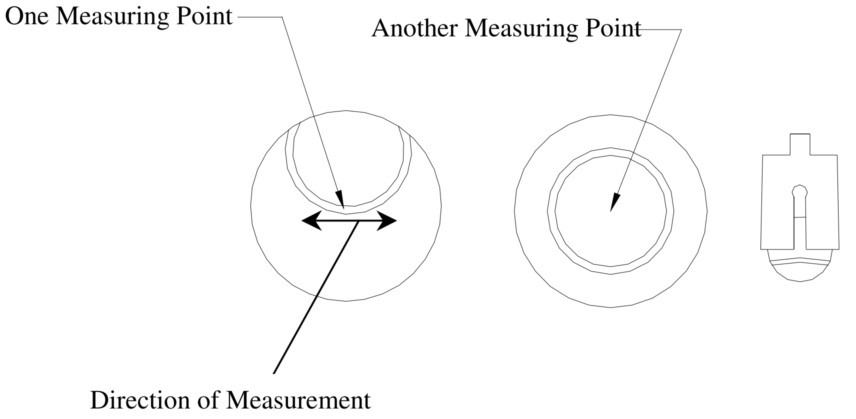
Table 3 Residual stresses measurement on self-finished balls

Description of the ball	**Residual Stress Value** (MPa)
A	-132.857(±)30.17
B	-76.742(±)15.56
C	-81.465(±)34.57
D	-21.276(±)10.50

Table 4 Residual stress measurement results before RCF test

Description of the ball after RCF test	Residual stress value (MPa)
A after 134.4 hours (181.4 million stress cycles), On the track	119.034(±)34.40
A after 134.4 hours (181.4 million stress cycles), At the centre	32.106(±)23.94
B after 100.7 hours (136 million stress cycles), On the track	174.208(±)34.46
B after 100.7 hours (181.4 million stress cycles), At the centre	23.674(±)24.94
B after 67 hours (90.5 million stress cycles), On the track	-269.925(±)56.01
B after 67 hours (90.5 million stress cycles), On the track, another measurement	-277.054(±)58.42
B 67 hours (90.5 million stress cycles), At the centre	57.699(±)30.18
C after 110.5 hours (149 million stress cycles), On the track	133.959(±)37.94
C after 110.5 hours (149 million stress cycles), At the centre	63.965(±)25.93
C after 44 hours (59.4million stress cycles), On the track	-45.543(±)14.50
C after 44 hours (59.4million stress cycles), At the centre	36.224(±)18.86
D after 132 hours (178 million stress cycles), On the track	110.326(±)38.46
D after 132 hours (178 million stress cycles), At the centre	78.199(±)22.01

Table 5 Residual stress measurement results after RCF test



(a) (b) (c)

Fig 1 Residual stress measuring points

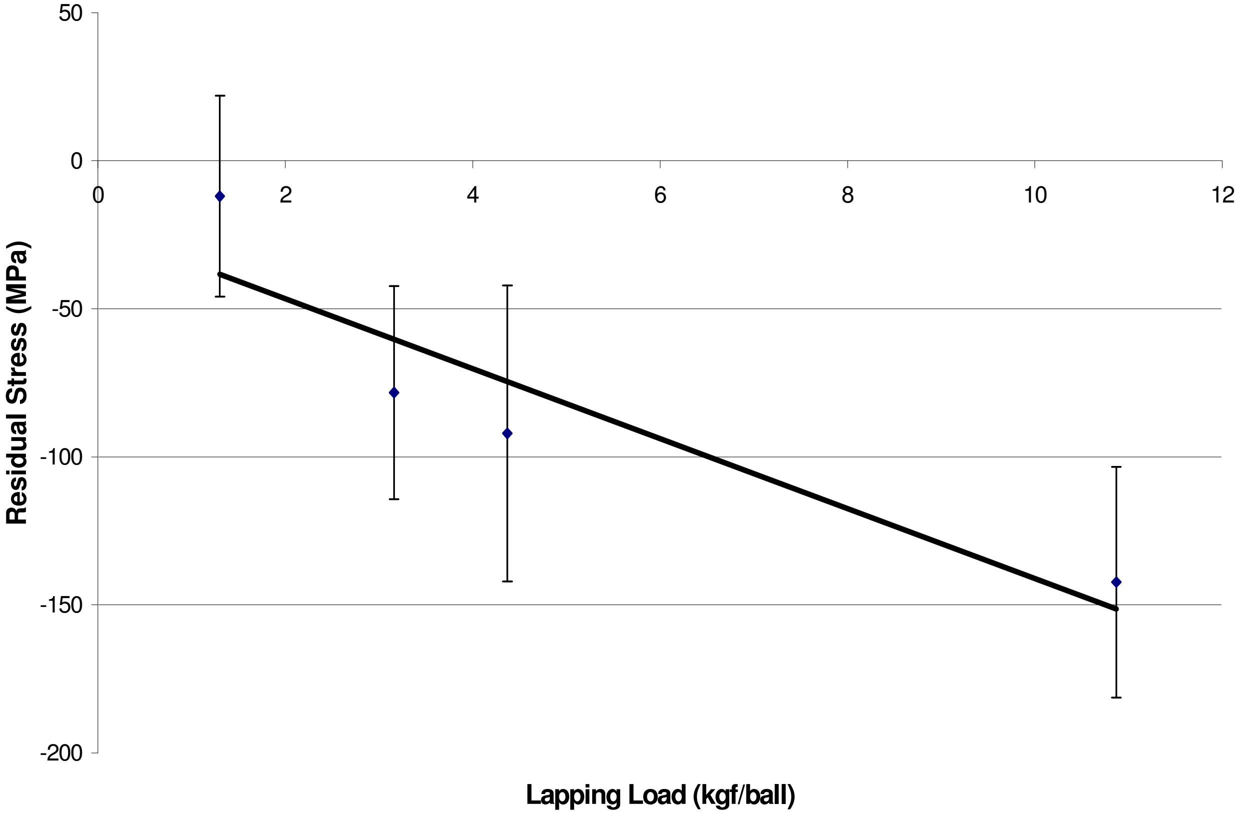


Fig 2 Residual stress versus lapping load